DESIGNING AN INNOVATIVE COMPOSITE ARMOR SYSTEM FOR AFFORDABLE BALLISTIC PROTECTION

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ABSTRACT

We will demonstrate a new design methodology, called Function-Oriented Material Design (FOMD), by designing an innovative composite armor system against ballistic and fragment penetration. A new composite armor concept, called BTR-*Ba*, is presented, which has three major subsystem modules: 1) a mosaic ceramic armor (MCA) frontal plate, 2) a biomimetic tendon reinforced (BTR) composite back plate, and 3) an optimized cable network supporting structure. The FOMD tool developed at MKP Inc. is extended in this research for designing ballistic-protective composite structures. This paper focuses on the frontal armor plate and back plate design problems with demonstration examples, including both results of the virtual prototyping and ballistic testing for proof-of-concept of the new armor concept and design methodology developed.

1. INTRODUCTION

A typical composite armor is composed of material layers made of fiber laminates, ceramics, rubbers, metals, etc. Most frequently the design variables in a composite armor design are limited to the material selection, order of the layers and the thickness of the layers. In this research, we investigate an innovative armor concept developed at MKP through optimizing three-dimensional material distribution using the FOMD technology developed at MKP. Figure 1 illustrates the composite armor concept with three major subsystem modules, and in Fig. 2 four design variables are considered in the frontal armor plate design process. Major projectile defeat mechanisms considered in the design include:

a) A hard top surface layer against initial impact of the projectile.
b) Optimally shaped pellets to disperse the impact force to the surrounding areas.
c) Proper bonding material to absorb impact energy and to limit crack propagation.
d) A cable network to further reinforce the integrity and reduce the impact force.

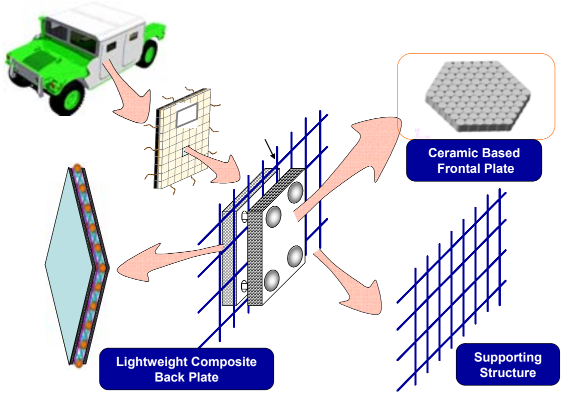

Figure 1. The new armor concept and design variables used in the frontal plate design process.

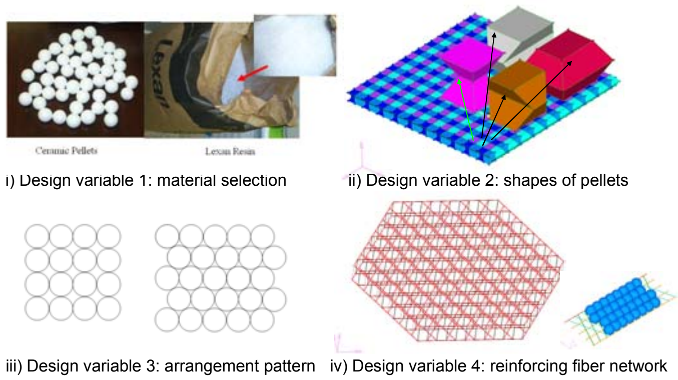

Figure 2. Design variables for the armor system

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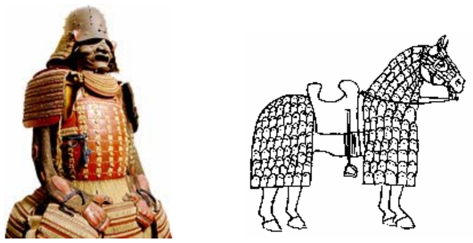
1.1 Advanced Composite Armors

The earliest armor technologies can be traced back to ancient times, when armor was used to protect soldiers and horses. Figure 3-a shows an ancient Japanese warrior armor, called Gusoku, developed around the 16th century. This armor was primarily constructed using bamboo, leather, cloth and metal. A variety of breastplate designs were in use, such as laced horizontal strips; large rectangular laced tiles; closely molded, riveted cuirasses of horizontal or vertical bands; and even European-influenced peaked breastplates of solid metal. The arms and neck were protected by small pieces of metal tied together with colorful strings. Horses were also covered with armor for protection in battle. The earliest horse armor was chain-mail, which was gradually replaced by plate armor that had moveable joints. Figure 3-b illustrates a lamellar armor used by Byzantine/Persian heavy cavalry (developed around the 12th century), which consisted of small plates laced together. The plates were made from hardened leather, horn, bone, layered felt, or in some cases, iron. The greatest advantage of these ancient armors was flexibility, as they could fit bodies with different shapes and sizes due to the way the armor was designed and fabricated.



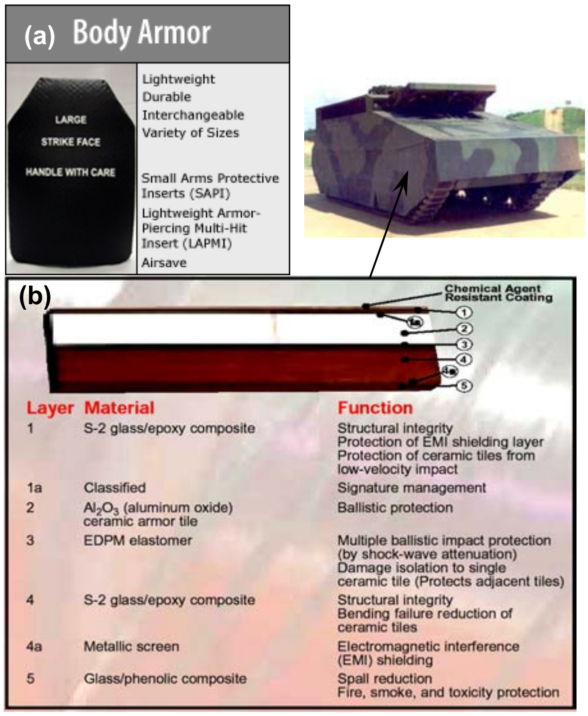
a) An ancient Japanese warrior armor
b) An ancient Byzantine/Persian horse armor

Figure 3. Ancient concepts of composite armors. (The greatest advantage of this armor is its flexibility. It conformed to different body shapes and sizes.)

Modern technologies have resulted in more effective armors to protect vehicles and soldiers (Figure 4). A concept useful to quantify the effectiveness of an armor is areal density, which is defined as the mass per unit area of a particular armor solution to defeat a particular threat.

Composite armor is usually provided in modules or tiles, which are composed of a mosaic of hard (ceramic) materials backed by softer but strong (composite) fibers embedded in organic matrices

The Advanced Composite Armor (ACA) and body armor have structural similarities and differences as shown in Fig. 4-a and 4-b. As described in references [Godinez-Azcuaga et al. and Bruchey et al.], two primary concerns for projectile defeat are: 1) compressive loading under the projectile; 2) deflection and back surface stress of the ceramic tiles under ballistic load. Although the first issue can only be addressed with new ceramic materials which are strong in compression, the second concern can be addressed through design improvement, for example using stiff and high flexural strength composite structures to support the ceramic tiles.



a) An advanced personal armor b) A future combat system with advanced composite armor (ACA), from (Fink, 2002)

Figure 4. Advanced Composite Armors. (Advanced composite armor is developed to achieve better areal density.)

Advanced composite armors (ACAs) are typically multi-layers consisting of ceramics, fiber-reinforced polymers, metallic screens, and possibly rubber materials. (Fink, 2002) These layers serve specific purposes in defeating projectiles and maintaining the structural integrity of the armor as well as addressing the interaction of the armor with the rest of vehicle structures.

The outer layer of the ACA is usually a fiber reinforced polymer to maintain structural integrity. It also protects the underlying ceramic from normal wear and tear. Ceramic material in the next layer has functions

such as destroying the tip of the projectile, distributing the impact load over a large area of the composite, and decelerating the projectile. The inner composite layers support the ceramic and perform other functions such as holding the ceramic debris together and further resisting the projectile. The performance of each layer significantly influences the overall performance of the armor. (Fink, 2002; Kaufmann et al., 2003)

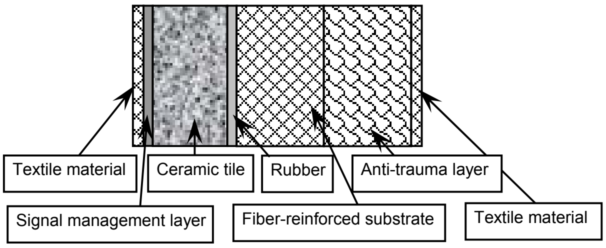


Figure 5. Typical design of composite armor.

1.2 Function-Oriented Material Design (FOMD)

The design methodology utilized in the present research is referred to as *function-oriented material design* (FOMD). FOMD was developed based on a breakthrough technique for the topology optimization of structural systems developed by Bendsøe and Kikuchi in 1988 (Bendsøe and Kikuchi, 1988) and known worldwide as the *homogenization design method*. With advanced optimization techniques, such as multi-domain and multi-step optimization methods, FOMD has extended capabilities for a wide variety of engineering problems, and has been successfully applied to the design of vehicle structures with improved static, NVH (noise, vibration, harshness), and crashworthiness performances.

An example is given in Figure 6 using FOMD, which can be utilized in this research for lightweight yet strong structures for ballistic protection. In the example, the intermediate structure between stiff tiles (such as those in a composite armor) and interior walls of a vehicle (inside crew compartment) can be designed with functionally gradient properties to be lightweight and high-performance. The intermediate structure improves the compatibility of very stiff tiles and the interior wall of a vehicle which can be considerably more flexible, and thus can help to defer delamination and to improve the performance of the whole structure.

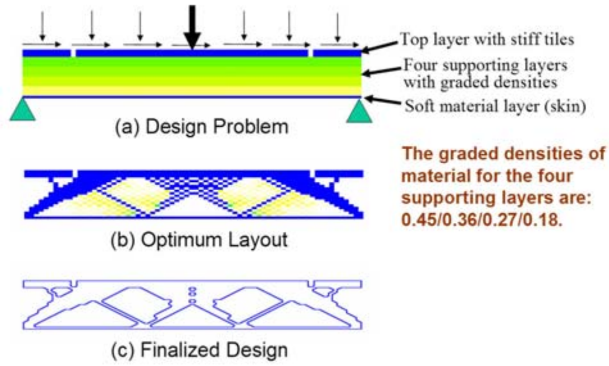


Figure 6. Lightweight functionally gradient structure design with stiffness/strength requirements

1.3 Design Strategy for Advanced Composite Armor

State-of-the-art composite armor design relies heavily on ballistic testing. If the traditional design approach was to be utilized, the armor concept presented would require a significant number of tests, resulting in a long developmental period with unacceptable cost. For example, to determine the optimal shape(s) of the ceramic pellets, a large number of samples would need to be fabricated and tested under various ballistic speeds and angles. In addition, only limited information can be obtained from each individual test due to the difficulty in measuring high-speed related phenomenon, and at the end of a test, one is left with only shattered fragments. Numerical simulation can provide much more detailed information from virtual ballistic tests. Considering these factors for different design tools, a combined design strategy is utilized in this research, as depicted in Figure 7. The combination of three tools will ensure a successful armor concept for defeating the projectiles. Among the three tools mentioned, the composite armor concept can be more optimally designed with an advanced design methodology and its associated CAE tool, such as FOMD (function-oriented material design) developed at MKP. FOMD is based on topological optimization, a revolutionary design technique for innovative structural and material designs. FOMD can be used to significantly extend the design space and simultaneously optimize both structural configuration and material usage in one design process for a complicated engineering design problem. With consideration of the fundamental projectile defeat mechanisms, including high-speed impact, wave propagation, and material damage in response to a ballistic impact, the advanced composite armor can be optimized to achieve the best performance/weight ratio, minimizing life-cycle cost at the same time.

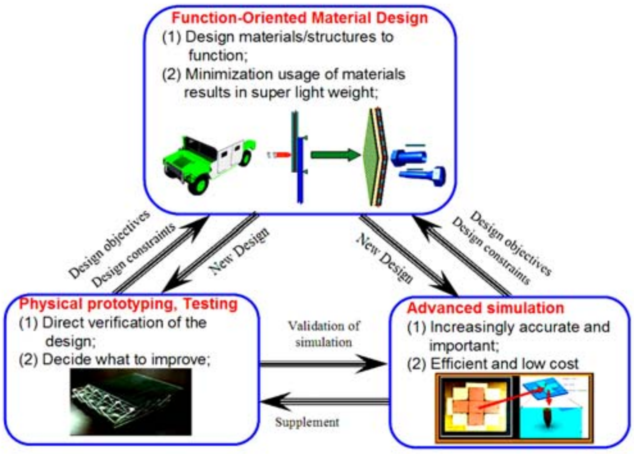
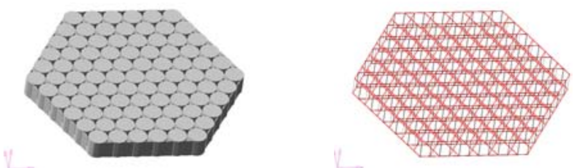


Figure 7. Design strategy for advanced ceramic armor

From our simulation and design process, an optimal material system was derived for the ceramic face plate, in which hard ceramic blocks function to defeat the projectile, and cables sustain tensile forces due to impact and bending of the face plate. Figure 8 illustrates a typical armor frontal plate concept (MCA) developed at MKP with a real-size physical prototype. It can be seen that the ceramic cylinders are arranged in close contact to each other. This hexagonal arrangement will reduce the chance of debris penetrating through the gaps between cylinders, distributes the impact load better to a larger neighboring area, and, also makes it easier to assemble a large piece of armor with an arbitrary body contour to a vehicle. To verify the concept design, numerical simulations have been conducted using LS-Dyna3D.



(a) Ceramic cylinders (b) Cable network

Figure 8. Typical design of face plate

2. MATERIAL MODEL

2.1 Ceramics Model

The most widely used material model for ceramics is the Johnson-Holmquist (JH2) ceramics model. (Johnson and Holmquist, 1999) This model has been implemented in several commercial software packages, including Epic, Autodyn, and LS-Dyna3D. This model is widely used in armor simulation and design, and many reports can be found in the literature. (e.g. Holmquist and Johnson, 2002; Cronin et al., 2003; Yen, 2002; Zaera et al. 2000) LS-Dyna3D is selected as the simulation tool because it is the most widely used general-purpose code for the problem. Many advanced material models and numerical methods are available in LS-Dyna3D. The material model (JH2) is named material 110 (*MAT_JOHNSON_HOLMQUIST_CERAMICS). Material parameters are adopted from the literature for the current research. Silicon carbide (SiC) is selected as the ceramic material, and material parameters are given as:

$$\rho = 3163\,Kg/m^3,\;\; G = 183\,GPa,$$
$$A = 0.96,\; B = 0.35,\; C = 0.0,\;\; M = 1.0,\; N = 0.65,$$
$$Ref\;\;Strain\;\;Rate\;(EPSI) = 1.0,\;\; Tensile\;\;Strength = 0.37GPa,$$
$$Normalized\;\;Fracture\;\;Strength = 0.8,$$
$$HEL = 14.567\,GPa,\;\; HEL\;\;\mathrm{Pr}essure = 5.9GPa,$$
$$HEL\;\;Strength = 13.0GPa,$$
$$D_1 = 0.48,\quad D_2 = 0.48,$$
$$K_1 = 204.785GPa,\;\; K_2 = K_3 = 0.0,\quad \beta = 1.0,$$

2.2 Fiber Reinforced Polymers (FRPs)

The same material model in Yen et al. (Yen, 2002) was selected for fiber reinforced polymer layers of ACA. The material parameters (for S2-glass/Epoxy plain weave) are given as:

$$\begin{array}{ll}
E_x = E_y = 24.1GPa & E_z = 10.4GPa \\
v_{xy} = 0.12 & v_{xz} = v_{yz} = 0.12 \\
G_{xy} = G_{yz} = G_{zx} = 5.9GPa & \\
S_{xT} = S_{yT} = 0.59GPa & S_{xC} = S_{yC} = 0.35GPa \\
S_{FS} = 0.55GPa & S_{FC} = 0.69GPa \\
S_{xy} = S_{yz} = S_{zx} = 48.3MPa & S_{xCR} = S_{xCR} = 0.10GPa \\
S = 1.4 & C = 0.1 \\
\phi = 40^0 & m = 4 \\
\rho = 1783Kg/m^3 &
\end{array}$$

3. VIRTUAL PROTOTYPING FOR FACE PLATE

The geometry and dimension of an ACA are shown in Figure 9. The projectile is assumed to be steel with conical-shaped tip and the geometry of projectile represents the core of a 7.62 mm AP bullet.

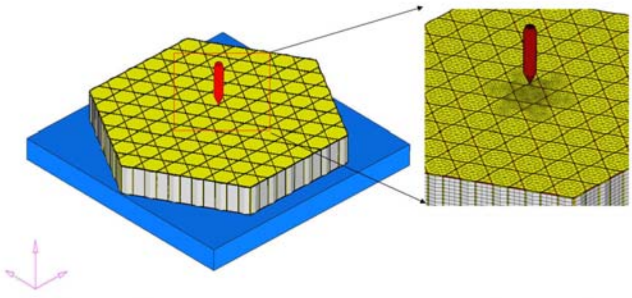


Figure 9. Simulated layout of ACA in finite element model

With this arrangement of ceramic pellets, the projectiles can hit any location. It is important that the performance of the system is similar wherever the projectile hits. Three representative locations were selected as the entry point of the projectile. One is in the center of a ceramic pellet. The second is located between two neighboring pellets, and the last is between three adjacent pellets. The locations are depicted in the following figure.

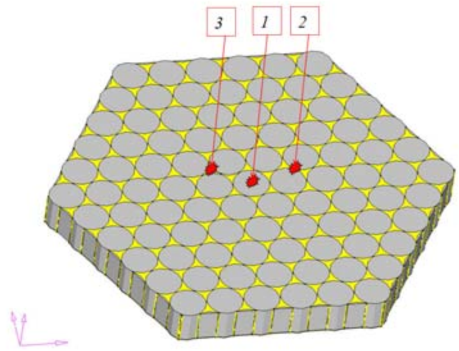
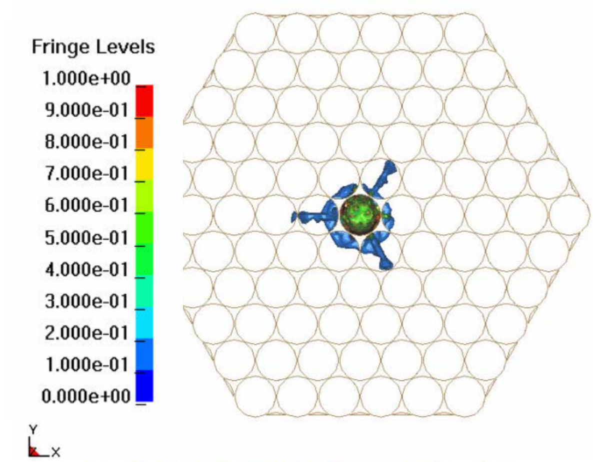
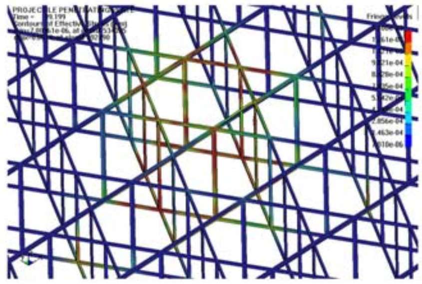


Figure 10. Three cases of simulation with different entry locations

Simulation Case I

In the first case, the projectile hits the center of a pellet, and the performance of the ceramic layer is expected to be the best. The simulation results are shown in Fig. 11. Results show that the projectile was destroyed by the pellet. The damage of ceramic pellets is limited to surrounding pellets. From the results, it was also observed that the cables provide reinforcements to the ceramic layer, which helps to increase the bending stiffness of the ceramic layer. Because the damage is localized, cable damage is not observed except at the entry point.





(a) Damage inside pellets after the hit (b) Stress distribution inside the cables

(c) Damage of projectile at different stages

Figure 11. Simulation results for the first case

From the above results, it can be seen that the armor concept defeated the assumed projectile. Damage to the ceramic material is restricted to the local area around the entry point. It is also shown that the cable network remains minimally damaged after the impact. The cable network helps to distribute the load to a larger area.

Simulation Case II

In the second case, the projectile hits the location at the middle of two neighboring pellets. It is expected that the performances of the ceramic layers would not be as good as the previous case. However, from the simulation, it is found that the ceramic layer functions almost the same as in the previous case. The impact process is illustrated in the following figure.

In Fig. 12, the damage and stress inside the cable network is depicted. It can be seen that the cable was broken at the site of impact, but elsewhere the cables are

almost intact, which could transfer the impact load to neighboring areas.

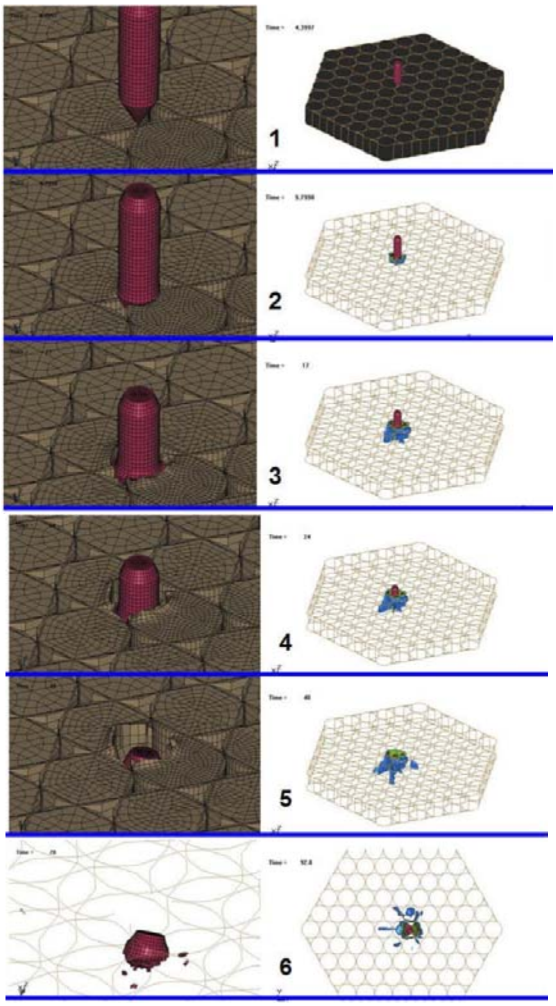


Figure 12. Ballistic impact of a steel projectile between two cylinders

Simulation Case III

In the third case, the projectile hits the gap between 3 neighboring pellets. It was expected to be the weakest location in the armor. However, from the simulation, it is found that the projectile could still be stopped. The projectile is jammed among the 3 pellets. At the same time, some debris did manage to hit the back plate, but was stopped there. (Figure 13)

4. DESIGN PROBLEM FOR BACK PLATE

4.1 Function analysis of back plate

The back plate supports the ceramic layer during the process of impact. This support will be important in helping the ceramic layer defeat the projectile. The back plate should have high bending stiffness to prevent excessive bending, which is an undesired deformation for the ceramic layer. At the same time, the back plate should have high bending strength to support the damaged ceramic material in place to continue to stop the projectile. At the same time, the back plate should be able to collect debris from projectiles and ceramic layer and to stop them from penetration.

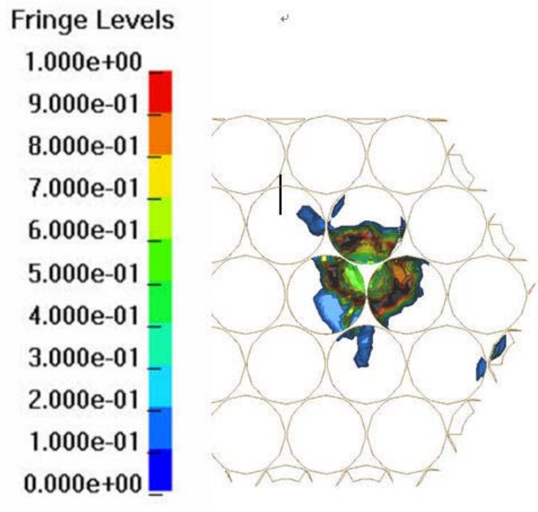


Figure 13. Damage inside the ceramic cylinders

Within the simulation results, the pressure acting on the back plate is plotted in Fig. 14 at 14.2 μS and 20.8μS. It can be seen that the back plate sustains a pressure distribution with a high peak at the mid point where the projectile hits the armor.

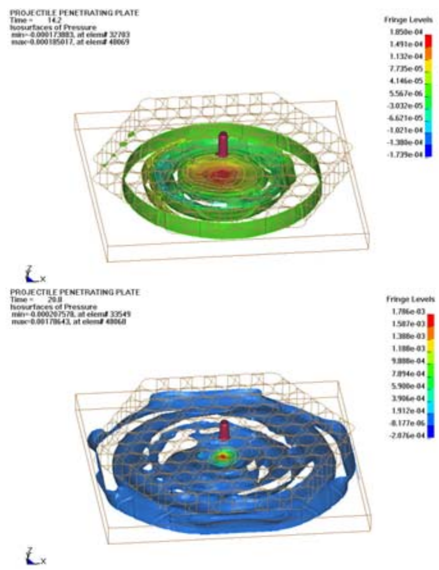


Figure 14. Pressure distribution inside the back plate during the impact process.

The concept of the pressure distribution depicted in Fig. 15, can help analyze the function of the back plate and can aid in the construction of the design problem.

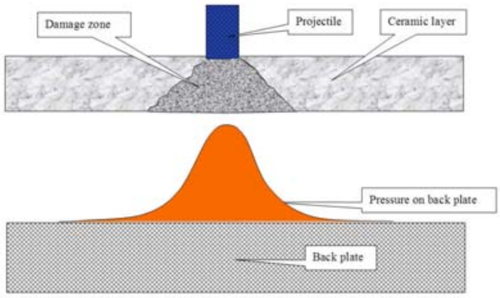


Figure 15. Impact force acting on the back plate

4.2 Back Plate Design

The back plate design problem can be defined as shown in Fig. 16-a, and the optimal design for the design problem can be obtained using the FOMD process, which is shown in Fig. 16-b. Figure 16-b shows that the two-dimensional design, which can be extended to a three-dimensional back plate design as shown in Fig. 17. The back plate is composed of Kevlar fabric, Kevlar ropes, with the stuffers made of different materials.

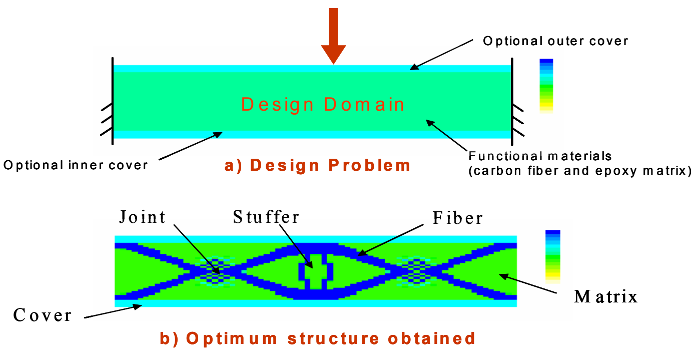


Figure 16. Design problem for back plate

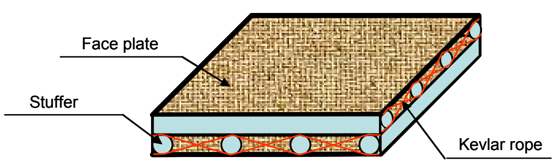


Figure 17. 3D design of back plate

5. PHYSICAL PROTOTYPING

In order to verify the design results, physical prototyping and ballistic testing were conducted. A typical result is shown in the following Figure 18. A 7.62x39mm M43 bullet was shot from a SKS rifle at the target. From Figure 18, it can be seen that damage was limited to a very localized area, and that the projectile was stopped. The debris of the projectile was stuck inside the face plate, and was recovered only with effort after the test. The ballistic test correlated our proposed concept and design procedure. It can be seen that this armor design can sustain multiple additional impacts.

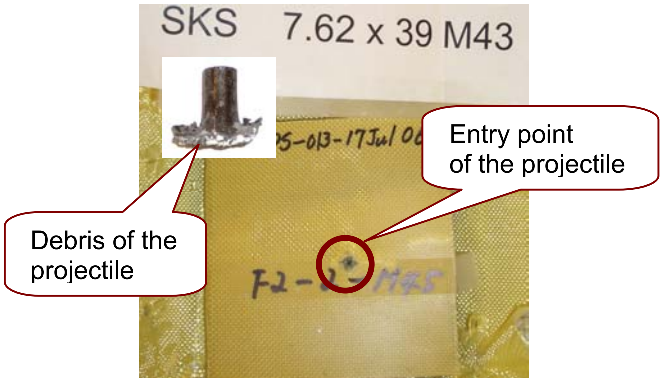


Figure 18. Coupon after ballistic test and remains of projectile

CONCLUSIONS

We proposed an advanced composite armor design process based on our unique capabilities in design, simulation and testing. The new armor concept will ensure optimization of each subsystem module in the composite armor system based on the functional requirements of the armor module. Using hybrid material design for the ceramic layer provides additional important design variables besides thickness, size, and materials. We have shown through virtual and physical prototyping that improved ballistic performance can be achieved through the design process. The back plate is an important part of the composite armor design. With the FOMD tool developed at MKP, the back plate can be designed to be sufficiently stiff, strong, and lightweight. The new BTR (Bio-mimetic Tendon-Reinforced) material concept can significantly improve the back plate design. We have developed a nonlinear cable network model, which can be used for effective design of the proposed supporting structure. Different design options will be further investigated and an optimal design will be determined in the Phase II program.

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